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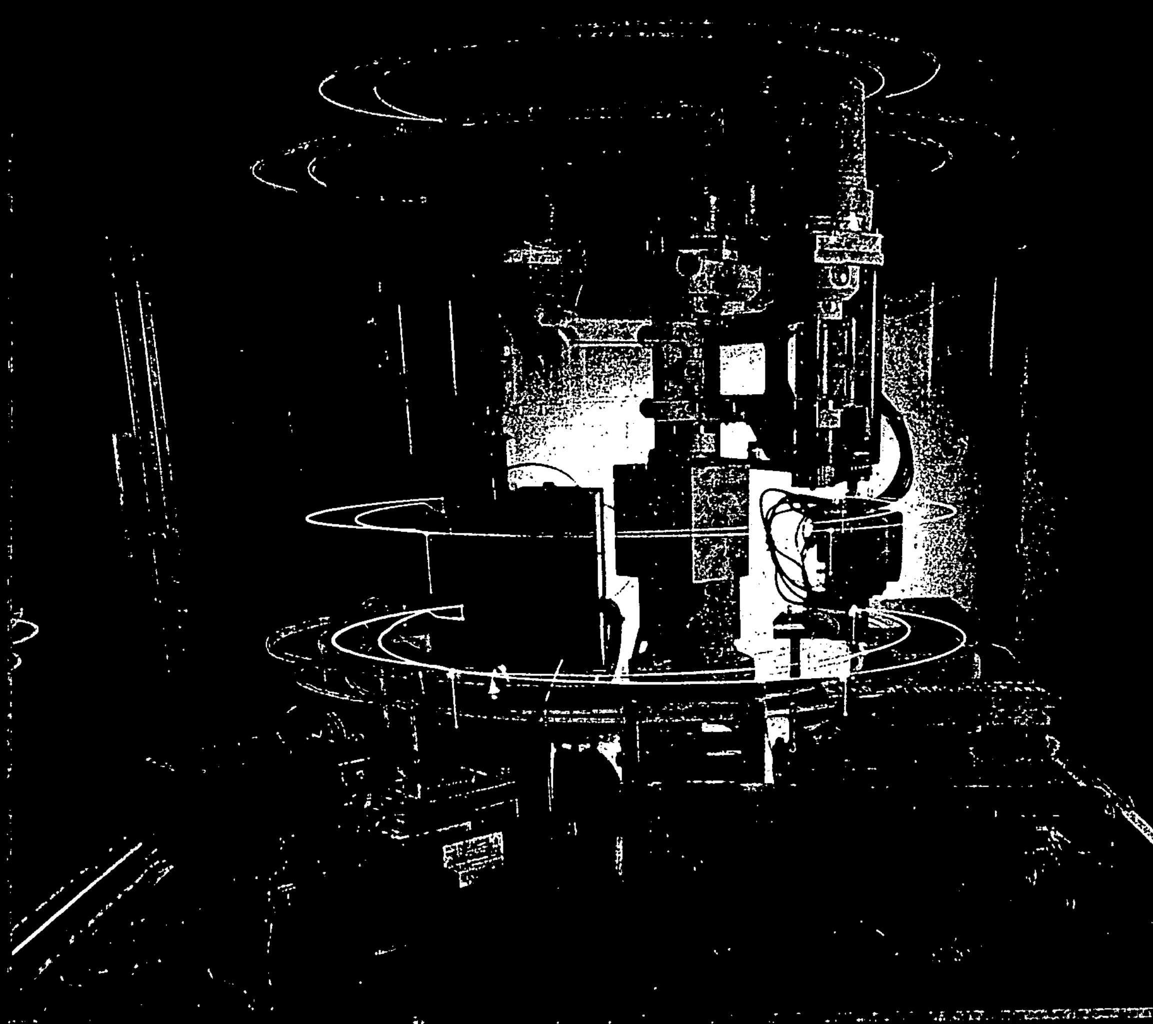
APPENDIX C

FEEDBACK CONTROL OF DYNAMIC SYSTEMS

THIRD EDITION



Gene F. Franklin • J. David Powell
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THIRD EDITION

Feedback Control of Dynamic Systems

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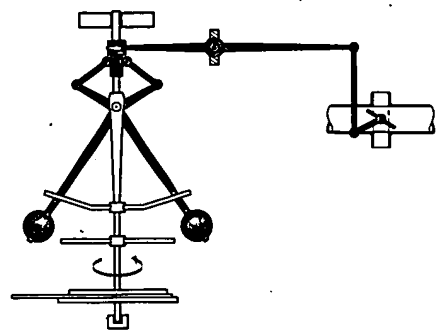
An Overview and Brief History of Feedback Control



A Perspective on Feedback Control

Control is a very common concept. The term refers to specific kinds of human–machine interactions. For example, in driving an automobile, it is necessary to control the vehicle in order to arrive safely at a planned destination. Such systems require **manual control. Automatic control** involves machines only, as in room-temperature control, where the temperature is controlled by a furnace in winter and an air conditioner in summer: Both machines are in turn controlled (turned on and off) according to a thermostat reading. From these specific scenarios we can generalize an engineering definition of control: **Control** is the process of causing a system variable to conform to some desired value, called a **reference value**. In the furnace-and-air-conditioner example, temperature is the system variable being controlled.

Control

An extensive body of knowledge common to both manual and automatic control has evolved into the discipline of control systems design, the subject of this book. More specifically, we are concerned with the special class of control systems that use feedback. **Feedback** is the process of measuring the controlled variable (for example, room temperature) and using that information to influence the value of the controlled variable.

Feedback

In this boo[illegible] shall call any operation to be controlled [illegible]*cess*. Examples are chemical, economic, and biological processes.

Systems. A system is a combination of components that act together and perform a certain objective. A system is not limited to physical ones. The concept of the system can be applied to abstract, dynamic phenomena such as those encountered in economics. The word system should, therefore, be interpreted to imply physical, biological, economic, and the like, systems.

Disturbances. A disturbance is a signal that tends to adversely affect the value of the output of a system. If a disturbance is generated within the system, it is called *internal*, while an *external* disturbance is generated outside the system and is an input.

Feedback Control. Feedback control refers to an operation that, in the presence of disturbances, tends to reduce the difference between the output of a system and some reference input and that does so on the basis of this difference. Here only unpredictable disturbances are so specified, since predictable or known disturbances can always be compensated for within the system.

Feedback Control Systems. A system that maintains a prescribed relationship between the output and some reference input by comparing them and using the difference as a means of control is called a *feedback control system*. An example would be a room-temperature control system. By measuring the actual room temperature and comparing it with the reference temperature (desired temperature), the thermostat turns the heating or cooling equipment on or off in such a way as to ensure that the room temperature remains at a comfortable level regardless of outside conditions.

Feedback control systems are not limited to engineering but can be found in various nonengineering fields as well. The human body, for instance, is a highly advanced feedback control system. Both body temperature and blood pressure are kept constant by means of physiological feedback. In fact, feedback performs a vital function: It makes the human body relatively insensitive to external disturbances, thus enabling it to function properly in a changing environment.

As another example, consider the control of automobile speed by a human operator. The driver decides on an appropriate speed for the situation, which may be the posted speed limit on the road or highway involved. This speed acts as the reference speed. The driver observes the actual speed by looking at the speedometer. If he is traveling too slowly, he depresses the accelerator and the car speeds up. If the actual speed is too high, he releases the pressure on the accelerator and the car slows down. This is a feedback control system with a human operator. The human operator here can easily be replaced by a mechanical, electrical, or similar device. Instead of the driver observing the speedometer, an electric generator can be used to produce a voltage that is proportional to the speed. This voltage can be compared with a reference voltage that corresponds to the desired speed. The difference in the voltages can then be used as the error signal to position the throttle to increase or decrease the speed as needed.

Servo Systems. A servo system (or servomechanism) is a feedback control system in which the output is some mechanical position, velocity, or acceleration. Therefore, the terms servo system and position- (or velocity- or acceleration-) control system are synonymous. Servo systems are extensively used in modern industry. For example, the completely automatic

operation of machine tools, together with programmed instructions may be accomplished by the use of servo systems. It is noted that a control system, whose output (such as the position of an aircraft in space in an automatic landing system) is required to follow a prescribed path in space, is sometimes called a servo system, also. Examples include the robot-hand control system, where the robot hand must follow a prescribed path in space, and the aircraft automatic landing system, where the aircraft must follow a prescribed path in space.

Automatic Regulating Systems. An automatic regulating system is a feedback control system in which the reference input or the desired output is either constant or slowly varying with time and in which the primary task is to maintain the actual output at the desired value in the presence of disturbances. There are many examples of automatic regulating systems, some of which are the Watt's flyball governor (for details, see Section 1–2), automatic regulation of voltage at an electric power plant in the presence of a varying electrical power load, and automatic control of the pressure and temperature of a chemical process.

Process Control Systems. An automatic regulating system in which the output is a variable, such as temperature, pressure, flow, liquid level, or pH, is called a *process control system*. Process control is widely applied in industry. Programmed controls such as the temperature control of heating furnaces in which the furnace temperature is controlled according to a preset program are often used in such systems. For example, a preset program may be such that the furnace temperature is raised to a given temperature in a given time interval and then lowered to another given temperature in some other given time interval. In such a program control the set point is varied according to the preset time schedule. The controller then functions to maintain the furnace temperature close to the varying set point.

Closed-loop Control Systems. Feedback control systems are often referred to as *closed-loop control systems*. In practice, the terms feedback control and closed-loop control are used interchangeably. In a closed-loop control system the actuating error signal, which is the difference between the input signal and the feedback signal (which may be the output signal itself or a function of the output signal and its derivatives), is fed to the controller so as to reduce the error and bring the output of the system to a desired value. The term closed-loop control always implies the use of feedback control action in order to reduce system error.

Open-loop Control Systems. Those systems in which the output has no effect on the control action are called *open-loop control systems*. In other words, in an open-loop control system the output is neither measured nor fed back for comparison with the input. One practical example is a washing machine. Soaking, washing, and rinsing in the washer operate on a time basis. The machine does not measure the output signal, that is, the cleanliness of the clothes.

In any open-loop control system the output is not compared with the reference input. Thus, to each reference input there corresponds a fixed operating condition; as a result, the accuracy of the system depends on calibration. In the presence of disturbances, an open-loop control system will not perform the desired task. Open-loop control can be used, in practice, only if the relationship between the input and output is known and if there are neither internal nor external disturbances. Clearly, such systems are not feedback control systems. Note that any control system that operates on a time basis is open loop. For example, traffic control by means of signals operated on a time basis is another example of open-loop control.

and-right motion). Th[illegible]ist attached to the end of the arm also ha[illegible]egrees of freedom, and the hand has 1 degree of freedom (grasp motion). Altogether the robot arm system has 7 degrees of freedom. Additional degrees of freedom are required if the robot body must move on a plane. In general, robot hands may be interchangeable parts: a different type of grasping device can be attached to the wrist to serve as a hand to handle each different type of mechanical object.

A servo system is used to position the arm and wrist. Since the robot arm motion frequently requires speed and power, hydraulic pressure or pneumatic pressure is used as the source of power. For medium power requirements, dc motors may be used. And for small power requirements, step motors may be used.

For control of sequential motions, command signals are stored on magnetic disks. In high-level robot systems, the playback mode of control is frequently used. In this mode, a human operator first "teaches" the robot the desired sequence of movements by working some mechanism attached to the arm; the computer in the robot memorizes the desired sequential movements. Then, from the second time on, the robot repeats faithfully the sequence of movements.

Robot hand grasping force control system. Figure 1–4 shows a schematic diagram for a grasping force control system using a force-sensing device and a slip-sensing device. If the grasping force is too small, the robot hand will drop the mechanical object, and if it is too large, the hand may damage or crush the object. In the system shown, the grasping force is preset at a moderate level before the hand touches the mechanical object. The hand picks up and raises the object with the preset grasping force. If there is a slip in the raising motion, it will be observed by the slip-sensing device and a signal will be sent back to the controller, which will then increase the grasping force. In this way, a reasonable grasping force can be realized that prevents slipping but does not damage the mechanical object.

Numerical control systems. Numerical control is a method of controlling the motions of machine components by use of numbers. In numerical control the motion of a workhead may be controlled by the binary information contained on a disk.

The system shown in Figure 1–5 works as follows: A magnetic disk is prepared in binary form representing the desired part P. To start the system, the disk is fed through the reader. The frequency-modulated input pulse signal is compared with the feedback pulse signal. The controller carries out mathematical operations on the difference in the pulse signals. The digital-to-analog converter converts the controller output pulse into an analog signal that

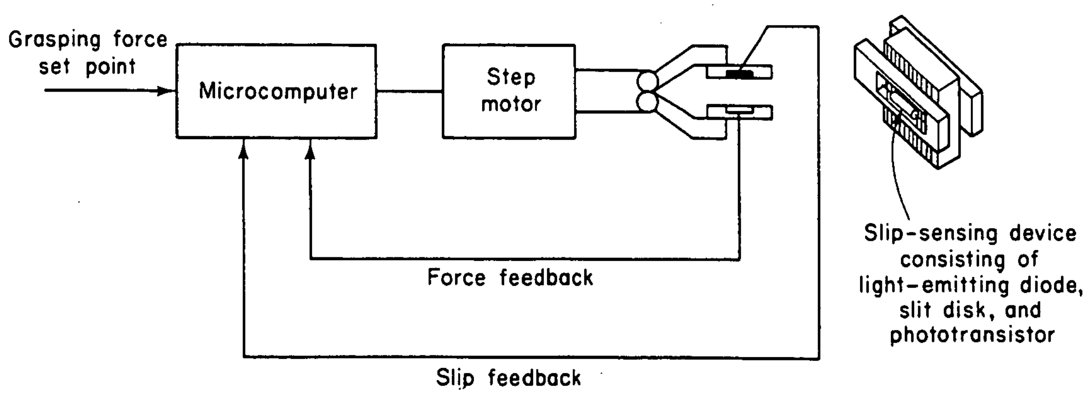


Figure 1–4
Robot hand grasping force control system.

amplifiers were multiplied many times. To solve the problem of reducing distortion, Black proposed the feedback amplifier. As mentioned earlier in connection with the automobile cruise control, the more we wish to reduce errors (or distortion), the more feedback we need to apply. The loop gain from actuator to plant to sensor to actuator must be made very large. With high gain the feedback loop begins to squeal and is unstable. Here was Maxwell's and Routh's stability problem again, except that in this technology the dynamics were so complex (with differential equations of order 50 being common) that Routh's criterion was not very helpful. So the communications engineers at Bell Telephone Laboratories, familiar with the concept of frequency response and the mathematics of complex variables, turned to complex analysis. In 1932 H. Nyquist published a paper describing how to determine stability from a graphical plot of the loop-frequency response. From this theory there developed an extensive methodology of feedback-amplifier design described by Bode (1945) and extensively used still in the design of feedback controls. Nyquist and Bode plots are discussed in more detail in Chapter 6.

PID control

Simultaneous with the development of the feedback amplifier, feedback control of industrial processes was becoming standard. This field, characterized by processes that are not only highly complex but also nonlinear and subject to relatively long time delays between actuator and sensor, developed **proportional-integral-derivative (PID) control**. The PID controller was first described by Callender et al. (1936). This technology was based on extensive experimental work and simple linearized approximations to the system dynamics. It led to standard experiments suitable to application in the field and eventually to satisfactory "tuning" of the coefficients of the PID controller. (PID controllers are covered in Chapter 4.) Also under development at this time were devices for guiding and controlling aircraft; especially important was the development of sensors for measuring aircraft altitude and speed. An interesting account of this branch of control theory is given in McRuer (1973).

An enormous impulse was given to the field of feedback control during World War II. In the United States engineers and mathematicians at the MIT Radiation Laboratory combined their knowledge to bring together not only Bode's feedback amplifier theory and the PID control of processes but also the theory of stochastic processes developed by N. Wiener (1930). The result was the development of a comprehensive set of techniques for the design of **servomechanisms**, as control mechanisms came to be called. Much of this work was collected and published in the records of the Radiation Laboratory by James et al. (1947).

Another approach to control systems design was introduced in 1948 by W. R. Evans, who was working in the field of guidance and control of aircraft. Many of his problems involved unstable or neutrally stable dynamics, which made the frequency methods difficult, so he suggested returning to the study of the characteristic equation that had been the basis of the work of Maxwell and Routh nearly 70 years earlier. However, Evans developed techniques and rules allowing one to follow graphically the paths of the roots of the characteristic

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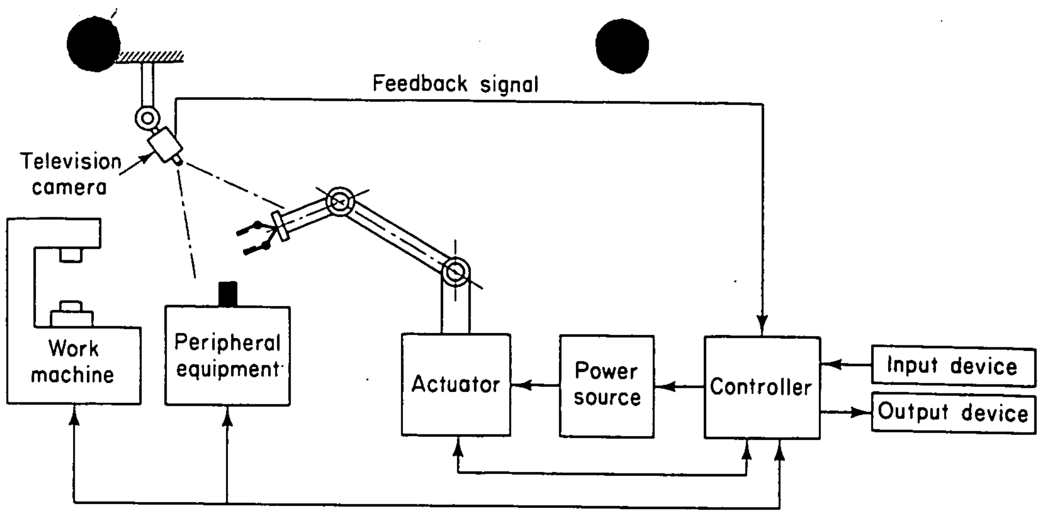

Figure 1–2
Robot using a pattern recognition process.

In a high-level robot, an optical means (such as a television system) is used to scan the background of the object. It recognizes the pattern and determines the presence and orientation of the object. A computer is necessary to process signals in the pattern-recognition process (see Figure 1–2). In some applications, the computerized robot recognizes the presence and orientation of each mechanical part by a pattern recognition process that consists of reading the code numbers attached to it. Then the robot picks up the part and moves it to an appropriate place for assembling, and there it assembles several parts into a component. A well-programmed digital computer acts as a controller.

Robot arm control system. Figure 1–3 shows a schematic diagram for a simplified version of the robot arm control system. The diagram shows a straight-line motion control of the arm. A straight-line motion is a 1-degree-of-freedom motion. The actual robot arm has 3 degrees of freedom (up-and-down motion, forward-and-backward motion, and left-

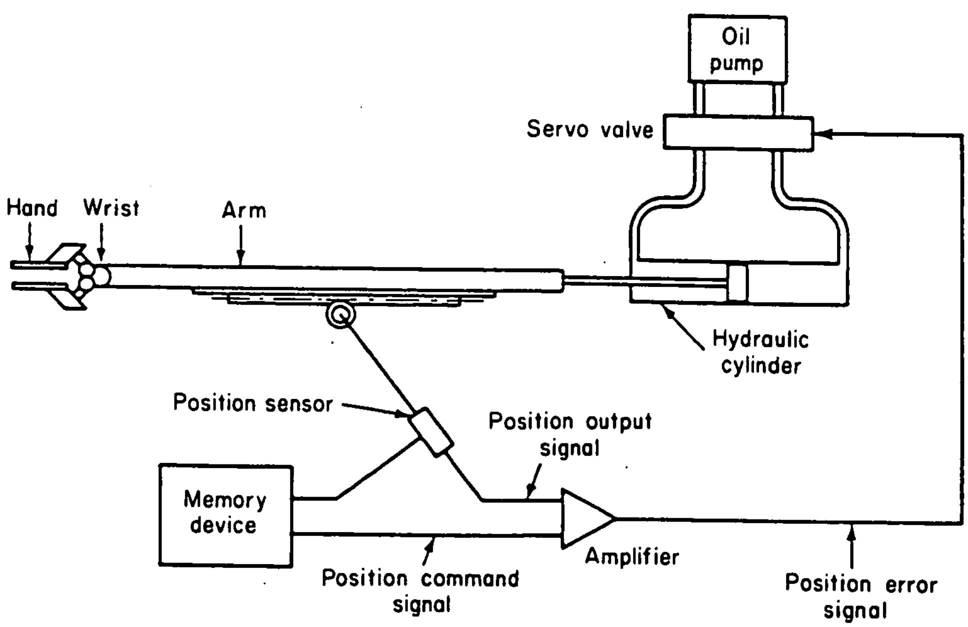

Figure 1–3
Robot arm control system.

and-right motion). The wrist attached to the end of the arm also h[illegible] degrees of freedom, and the hand has 1 degree of freedom (grasp motion). Altogether the robot arm system has 7 degrees of freedom. Additional degrees of freedom are required if the robot body must move on a plane. In general, robot hands may be interchangeable parts: a different type of grasping device can be attached to the wrist to serve as a hand to handle each different type of mechanical object.

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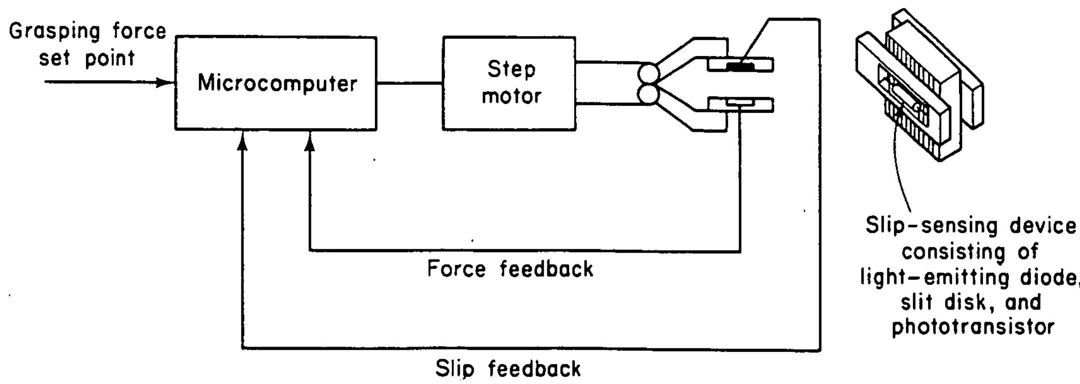

Figure 1–4
Robot hand grasping force control system.